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Biosynthesis for the Production of Fuels in an Overseas Theater

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Biosynthesis for the Production of Fuels in an Overseas Theater

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SUMMARY

PROBLEM

To investigate the feasibility of biosynthesis for the production of fuels for Army use in a theater of operations (TO).

FACTS

Modern military forces have large and increasing requirements for fuel because of the growing demands of mechanization and mobility. The supply of fuels to military forces in the field involves long and vulnerable lines of communication (LOC) and large commitments of transport.

Production of fuels in a TO has the potential for alleviating the logistic burden of both intra- and intertheater movements.

The technical feasibility of biosynthesis for the production of hydrocarbon and alcohol fuels has long been established.

DISCUSSION

Hydrocarbons and alcohol are produced indirectly by anaerobic breakdown of organic matter. Liquid methane and ethyl alcohol are fuels of high heating value compared with gasoline and may be attractive for Army use in a TO.

This paper considers two schemes for methane production: fermentation of organic matter and bioelectrochemical reduction of carbon dioxide. The fermentation schemes discussed require relatively simple and inexpensive apparatus that can be constructed in a short time and requires little maintenance effort. However, this study does not consider specific design features and material requirements for such facilities. The energy required for maintaining the fermentation process does not consume a significant fraction of the energy output. Space for fermentation can be provided by pits dug in the earth so that the earth's heat reservoir may be utilized.

Wood is not a practical source of methane because it is not uniformly distributed over the earth's surface and therefore may not be available in sufficient quantity in a particular TO. Moreover, for significant fuel production, extensive logging operations that require heavy hauling equipment and a large manpower outlay are necessary. Direct combustion of wood yields more energy (per pound of wood) than does the methane produced by the fermentation process. Consequently, biosynthesis of methane from wood is unattractive.

SUMMARY

Human waste and garbage are good sources of methane since they are universally available where military forces are located. Such material is easily collected and processed in base or reserve areas, where sewage and water supply complexes exist. However, the amount of raw material available for processing is too small for significant fuel production.* This conclusion is based on data obtained from municipal sewage-treatment plants where conversion efficiency is low. Even at 100 percent conversion efficiency the amount of human waste and garbage does not yield a logistically significant amount of methane. Biosynthesis of methane from either garbage or feces is unattractive.

Bioelectrochemical synthesis of methane is another means of using electric power to produce a fuel. Carbon dioxide is the most critical raw material for this process, and obtaining it by combustion of petroleum products, withdrawal of carbonates from sea water, or fractionation of air is unattractive. On the other hand, combustion of mineral carbonates and organic matter (such as wood) for carbon dioxide is promising. Thus the bioelectrochemical production of methane, using nuclear reactors or conventional plants to produce electric power, may be a promising method of producing fuel in a TO if improved sources of carbon dioxide are developed.

The fermentation of various substrates to produce ethyl alcohol is also considered. Raw material and manpower requirements for production of ethyl alcohol in the field are much less than those for methane fermentation. Wood and grain are the most attractive raw materials for alcohol fermentation. However, the large energy requirement for alcohol purification reduces the net energy available to an unattractive level.

CONCLUSIONS

1. Biosynthesis of hydrocarbon and alcohol fuels from fermentation of organic matter does not yield logistically significant amounts of fuel for Army operations.

2. Bioelectrochemical production of methane in a TO may be a promising means of reducing the Army's fuel logistic burden if better methods for obtaining carbon dioxide become available.

*In this study, fuel consumption is taken to be 20/lb/man/day. Substitution of 20 percent of this amount by a biosynthesized fuel is considered to be logistically significant.

BIOSYNTHESIS FOR THE PRODUCTION OF FUELS
IN AN OVERSEAS THEATER

ABBREVIATIONS

LOC	lines of communication
OCofT	Office, Chief of Transportation
POL	petroleum, oils, and lubricants
RAC	Research Analysis Corporation
TO	theater of operations
USAF	United States Air Force

INTRODUCTION

The purpose of this paper is to investigate the feasibility of biosynthesis for the production of hydrocarbon fuel and alcohol for Army use in a TO. This evaluation was done as part of the study RAC undertook at the request of the Chief of Transportation to investigate the operational feasibility of unconventional energy sources for overseas fuel production.[1]

In addition to nuclear power, the RAC study included nonnuclear energy sources. Nonnuclear energy sources discussed herein for production of Army fuels are biological fermentations and "bioelectrochemical" synthesis. This paper analyzes briefly some of the gross features of these systems. All calculations are based on requirements for 1000 men.

Methane is the only hydrocarbon known to be produced directly from the fermentative processes of certain microbes. It is a common constituent of gases evolved in sewage sludge digestion, decomposition of organic matter in swamps and bogs, and digestive processes of certain animals. Microbial decomposition of organic matter under anaerobic (restricted oxygen) conditions has been studied for over 60 years.[2] Gases rich in methane have been used for heating and electric power production in sewage-treatment plants for almost a century. Known originally as "illuminating gas" and later as "sludge gas" or "marsh gas," such a mixture is about 70 percent methane and 30 percent carbon dioxide with traces of carbon monoxide, hydrogen sulfide, and hydrogen.

Methane may be used in existing vehicle engines with only minor modifications in carburetors and manifolds. Likewise for cookstoves and ovens little alteration is necessary for conversion to methane.

Alcohols are produced commercially through the metabolic activities of yeasts, molds, and bacteria, and from ethylene, a petroleum by-product. Fermentative organisms differ greatly in morphology, size, method of reproduction, growth requirements, substrate specificity, and other aspects. They are similar, however, in that they all produce biochemical catalysts (enzymes) by which they catalyze certain reactions. Alcohols are the best-known and largest class of substances produced industrially by fermentation; specifically ethyl alcohol is produced in the largest volume.[3]

Alcohol has been used successfully to power spark and compression-ignition engines for over 40 years; it has also been used in fuel-injection engines. Formerly, alcohol-burning engines were characterized by poor low-speed performance and low power output (because of uneven fuel-air mixing), but redesign of intake manifolds and carburetors lessened these problems.

Alcohol-burning engines have an increased operating life because of lowered combustion temperatures, which reduce the amount of friction-causing combustion products. However, acetic acid and formic acid tend to form after engine shutoff, but this, too, is not an insurmountable problem. Alcohol can be blended with conventional fuels, which produces a significant increase in power and efficiency.

If a military force could efficiently produce fuels such as methane or alcohol in the field, its self-sufficiency would increase, and significant savings in manpower, money, and equipment needed to support military forces overseas might be obtained.

TECHNICAL CONSIDERATIONS

As with any biochemical reaction, the rate of reaction depends on temperature, moisture, degree of acidity, ecological factors such as concentration and types of organisms, and nutritional factors such as concentration and types of vitamins and solids.

Generally, biochemical processes do not reach peak activity instantaneously. Rates of specific microbiological processes closely follow growth and multiplication rates of the population being studied.

In methane fermentation an appreciable lag time is required to build up a microbial population capable of appreciable methane output. In contrast, bioelectrochemical reactions require no lag time for microbial growth. The presence of an adequate concentration of organisms and raw materials under the stimulus of an electrical current is sufficient for rapid attainment of peak methane generation.[4]

Chemical reactions such as fermentations occur at rates indicative of proportional molecular interactions, but electrochemical reactions such as the bioelectrochemical synthesis of methane occur at about 100 times the rates of molecular reactions.[4] Therefore, bioelectrochemical systems that match fermentation outputs can be made much more compact.

Ethyl alcohol is a high-energy fuel that can be produced by the fermentative activities of yeasts and other organisms. Any material rich in cellulose, starch, or sugar is a potential substrate for alcohol fermentation. The potential yield of alcohol from cereals is well defined, mainly because of the efforts of whiskey distillers to optimize alcohol output. The average alcohol output from cereal grains is 2.5 gal/bu/day, and this is the basis for estimating grain alcohol capability and processing requirements.

Much alcohol is produced from hydrolyzed wood in many countries.[3] Although the fermentable sugar potentials of various tree species differ somewhat, 1 lb of wood may produce as much as 0.16 lb of ethyl alcohol per day at 100 percent efficiency.[3]

A gross estimate of the alcohol potential of plant foliage is also made. At 100 percent conversion efficiency, 1 lb of foliage produces 0.02 lb of ethyl alcohol.

Alcohol is a liquid at normal temperature and pressure, but methane is a gas under such conditions. As a gas, methane cannot compete with ethyl alcohol for volumetric heat content, and even when the volumetric heat content of methane is greatly increased by liquefaction, it nevertheless remains less than that of alcohol (App A). Bulky pressurized or insulated containers

are necessary when handling compressed or liquefied methane, respectively. However, ethyl alcohol can be handled in standard gasoline containers.

BIOSYNTHESIS OF METHANE

When plant material is fermented by methane bacteria, cellulose is the main source of methane. When organic matter is decomposed in the gastro-intestinal tract of animals and in sludge digestors of sewage-treatment plants, fatty acids and other organic acids are the sources of methane. In general, methane is produced by the following reactions:

$$4HCOOH \rightarrow CH_4 + 3CO_2 + 2H_2O \quad (1)$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \quad (2)$$

$$2C_2H_5OH + 2H_2O + CO_2 \rightarrow 2CH_3COOH + CH_4 + 2H_2O \quad (3)$$

In reaction 1, fatty acids are decomposed directly to methane; carbon dioxide formed in this reaction is reduced to methane as shown in reaction 2. In reaction 3, alcohols are dehydrogenated to acids, and the carbon dioxide is reduced to methane. Also the organic acids (e.g., CH_3COOH) may be dehydrogenated to form methane and additional organic acids.

It has been stated that manyfold increases in methane output can be expected and that tenfold yield increases are sought.[5] In this analysis it is assumed that during the time frame of reference for this study (1965–1975), methane yields will be doubled and digestor detention periods will be shortened to 10 days for wood substrate and 1 day for human wastes.

It might be necessary to apply external heat to the fermenting substrate for temperate-zone operations during the cold season to maintain the microbial population, but no heating requirement is foreseen for fuel production in tropical or subtropical areas. In this analysis it is assumed that adequate substrate temperatures can be maintained regardless of climate or season.

The gas mixture evolved from methane fermentation is composed of compounds differing greatly in heat content. Methane can be separated from the mixture in gaseous or liquid form. The energy density of methane gas can also be increased by compression. When compared with gasoline for volumetric heat content, however, pressurized methane is decidedly inferior. One volume of pressurized methane (750 psi) has only 5 percent of the energy content of an equal volume of gasoline (App A). If a military force changed from a gasoline to a pressurized-methane fuel system, the volume adjustments necessary at every stage of distribution would be staggering. To provide the gasoline energy equivalent, the capacities of storage tanks, pipelines, delivery vehicles, and vehicle fuel tanks would have to be increased 20-fold to maintain present vehicle range and refueling frequency.

Methane can also be separated as a liquid from fermentation products by taking advantage of the discrete, well-separated liquefaction temperatures of the components (App A). Through liquefaction, gases like methane can be not only purified but also made much more dense energetically. However, energy

is required to liquefy methane (App B). About 2700 Btu is required to liquefy 1 lb of methane; this is 13 percent of its heat content. If the product fuel is used to power liquefaction equipment, then 18,300 Btu is available for every pound of fuel produced. This amounts to almost 60 percent of the heating value of an equal volume of gasoline as compared with less than 5 percent for pressurized methane. Thus, only liquid methane is considered in this study.

The Army now has equipment for liquefying air, hydrogen, nitrogen, and carbon dioxide but has no equipment designed for methane liquefaction. However, no major redesign of present equipment is necessary to convert to methane liquefaction.[6]

METHANE FROM FERMENTATION OF PLANT MATERIAL

Less is known in a practical way about methane fermentation of wood than about fermentation of sewage. Theoretical methane yields from wood have been computed to be 0.18 lb of methane per pound of wood.[5] Laboratory experience, however, has shown that only 0.013 lb of methane is produced per pound of wood.[5] It has been stated that the experimental yield can be doubled by the addition of specific fermentation enzymes.[7] In this study a wood fermentation system was analyzed on the basis of theoretical output since little research has been done on actual yields.

The energy content of liquid methane is 1.1 times as great as that of gasoline on a weight basis (App A). Hence about 19 lb of methane per man per day is equivalent to the average requirement of 20 lb/man/day. For a 1000-man force $19 \times 1000 \times (1/0.18)/2000 = 53$ tons of wood would be required daily if total fermentation occurred in 1 day. In contrast, 10 tons/day of POL will support 1000 men under average conditions. Since at least 10 days are required to attain complete fermentation of wood, 530 tons of wood must be processed the first day to attain a 1-day fuel output for 1000 men.

If batchwise operations were adopted, 530 tons of fresh substrate must be emplaced every 10 days, or fresh timber prepared at the rate of 53 tons/day (one-tenth of the first-day requirement) during the detention period in order to collect substrate for the following production cycle. A complete and abrupt substrate change would temporarily stop biological activity, whereas the gradual incorporation of fresh material would have minimal effect on these processes. The greatest potential for obtaining immediate methane output is the development of appropriate concentrated enzyme preparations.

Anaerobic degradation of wood to produce methane is an inefficient means of obtaining heat energy. The theoretical yield of 1 lb of wood is 0.18 lb of methane, which is equivalent to $0.18 \times 21{,}000 = 3900$ Btu. Direct combustion of wood (beech, birch, oak, or pine) yields approximately 8600 Btu/lb.[8] Therefore it is more attractive to burn the wood directly in vehicles than to synthesize methane.

METHANE FROM HUMAN WASTE

This study of methane from human excreta and garbage is based on the experiences of municipal sewage-treatment plants.[9-11] In the past many sewage

plants treated waste for the main purpose of producing methane for fuel.[1,12] Today, however, their primary mission is generally considered to be digestion of raw sewage to a state conducive to minimum water pollution, though a few companies have become successful dealers in organic fertilizers made from sludge cake.

Organisms that attack wood carbohydrate to produce methane and carbon dioxide gases can equally well degrade human waste, releasing the same gases. A fermentation system using a wood and waste mixture might be more attractive than each system operating separately, and this is considered later.

Sludge digestors in municipal facilities are constructed with a volume allowance of 3 cu ft/capita.[13] A 1000-man force would therefore require 3000 cu ft of digestor volume.

Sewage is degraded much faster than wood chips. In fact a minimum of only 24 hr is required for the complete degradation of certain wastes to carbon dioxide and methane.[2] Like wood digestors, simple chambers lined with a waterproof material suffice for sewage fermentation.

In order to determine the daily per capita output of methane, data were obtained from sewage-treatment plants of two cities having little industrialization.[10,11] Industrial wastes contribute significantly to sewage-treatment load, and therefore waste volume determinations for industrial cities do not reflect true per capita waste factors.

From an assumed waste solids output of 0.4 lb/person/day, sludge gas is produced at the rate of about 4 cu ft/lb solids/day.[10] When garbage is included, the waste solids output per capita increases to about 1 lb/day and gas output is therefore about 4 cu ft/man/day. If the sludge gas is about 70 percent methane the daily per capita output of methane is about 3 cu ft. With further research, considerable improvement in methane yield is possible; today the primary mission of sewage-treatment plants is generally waste disposal and not methane generation. Recently there have been increased efforts to improve the yields of methane from sewage sludge. Experiments have shown that methane output can be increased twofold by the addition of specific cellulose-splitting enzymes to the substrate.[7] Methane output is considered here for the 1965–1975 period and is therefore taken to be 6 cu ft/man/day. This yield corresponds to $6 \times 0.045 = 0.27$ lb/man/day of methane, or $0.27 \times 21{,}000 = 5700$ Btu/man/day (or 5700 Btu/lb/day) of energy available from decomposition of human waste.

For an Army average energy requirement of 400,000 Btu/man/day, methane energy availability meets only $5700/400{,}000 \times 100 = 1.4$ percent of the requirement. Regardless of the potentially high unit yield of methane from human waste, the quantity of substrate available per capita is not sufficient. Because waste fermentation fails technically it is not considered further in the operational analysis.

BIOELECTROCHEMICAL SYNTHESIS OF METHANE

Biochemical reactions such as those that occur in the fermentation processes discussed above are relatively slow. They usually proceed most rapidly under moderate environmental conditions: room temperature (25 to 35°C) and atmospheric pressure. Other processes for methane production involve a

catalyzed reaction of carbon dioxide with hydrogen at high temperature and pressure. Carbon dioxide for this reaction could be obtained from natural sources and hydrogen from electrolysis of water.[4]

Methane bacteria, capable of combining biochemically liberated hydrogen with carbon dioxide, produce methane at a rate too slow to be attractive. Preliminary calculations based on biosynthesis of methane with electrolytically produced hydrogen indicate that the rate of synthesis, though greater than in methane fermentation reactions, is nevertheless prohibitively low.

Recent advances in biochemical electrode construction indicate that increased efficiency results from a combination of the electrolytic process with the biologically induced hydrogen-utilization process.[4] Carbon dioxide is converted to methane in a bioelectrochemical cell without the liberation of free hydrogen, since the hydrogen, when liberated from water, is combined immediately with carbon.

The methane bioelectrochemical system is shown schematically in Fig. 1. The cell (A) should produce about 10 lb of methane per day per cubic foot of

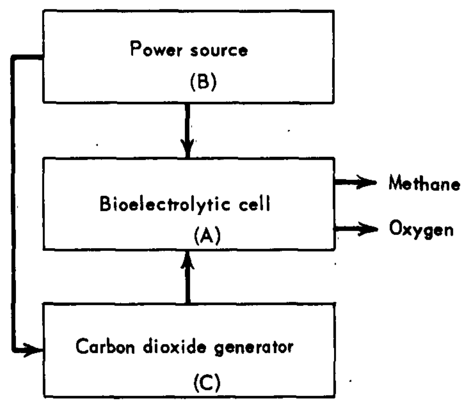

Fig. 1—Schematic of the Bioelectrochemical System[4]

cell.[4] Although power requirements for such a cell might be as high as 30 kwh per pound of methane produced, the theoretical requirement of 9 kwh/lb was used in determining requirements.[4] A power source (B) for a field-scale system might use Army reactors now under development. Alternatively, engine-generator sets could serve as sources of electrical power. Such generators require fuel, and if methane were used the net fuel available for vehicles would be reduced proportionately.

Resources

The most critical raw materials are wood, mineral carbonates, natural gas or oil, and water. Certain autotrophic methane bacteria are capable of metabolizing molecular hydrogen and carbon dioxide, forming methane and water, as shown in reaction 4.[4]

$$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O; \ \Delta F = -31.3 \text{ kcal} \quad (4)$$

Carbon dioxide can be obtained by the combustion of wood, mineral carbonates, oil, natural gas, gasoline, etc. Dolomite and limestone deposits and saline water are rich in mineral carbonates. Hydrogen is obtained from water.

The requirement for carbon dioxide is large, and it must be obtained from sources within the TO. Water, though not required in as great a quantity as carbon dioxide, must also be procured in the theater. The nutrient requirement is small,[4] so that the nutrients can be easily transported.

Other resources such as manpower, electrical power, and equipment must be readily available. Requirements for men and machinery are discussed in the operational analysis.

Carbon Dioxide. Of the 19,000 lb of methane required daily by 1000 men, 12/16 or 14,250 lb is carbon. Carbon dioxide is 12/44 carbon by weight, so that 52,800 lb of carbon dioxide must be produced each day at 100 percent efficiency to meet the methane requirement. However, the bioelectrochemical process is 67 percent efficient at a theoretical electrical potential of 1.5 v,* so that a minimum of 52,800/0.67 = 78,800 lb of carbon dioxide per day is required.

Air is rich in nitrogen and oxygen but is a rather poor source of carbon dioxide. Even though the carbon dioxide concentration is very low (0.04 percent by weight), air is readily available and easily collected. Carbon dioxide can be removed by passing air over monoethanolamine.[14] The oxide-amine complex can then be heated to drive off pure carbon dioxide. On the basis of an air density of 0.08 lb/cu ft,[15] $78.8/(0.004 \times 0.08) = 2.5 \times 10^6$ cu ft of air per man per day must be processed to supply carbon dioxide for methane synthesis. To process air for 1000 men (2.5×10^9 cu ft), high-rate air blowers such as turbojet engines are necessary. Certain engines, under normal power at sea level, have a throughput air capacity of 255 lb/sec or 255/0.08/86,400 sec/day = 2.8×10^8 cu ft/day.[16] If air is drawn at a rate sufficient to provide carbon dioxide for the methane synthesis requirement, $1000 \times 2.5 \times 10^6/2.8 \times 10^8 = 9$ engines in full-time operation are necessary.

Turbojet engines for air collection are unattractive because they consume jet fuel at a very high rate. If each engine consumes fuel at the rate of 8500 lb/hr, then nine engines in operation for 1 day consume the energy equivalent of an 85-day average gasoline supply for 1000 men.† It is likely that any other blower system capable of meeting air intake requirements will also have a high specific fuel-consumption rate and thus be as unattractive as the turbojet system.

Barge-mounted or shore-based synthesis facilities can draw saline water through their machinery to extract carbon dioxide from the mineral carbonates present. The carbonates can be precipitated from solution and the carbon

*At the theoretical potential for this process (1.5 v), 1.5×14.3 amp-hr/g $\times$ 1 kwh/1000 amp-hr $\times$ 454 g/lb = 9 kwh or 9×3413 Btu/kwh = 30,700 Btu are required for synthesis of 1 lb methane. The ratio of the energy content of 1 lb methane (21,000 Btu) and the input energy for methane synthesis (30,700 Btu/lb) gives a theoretical process efficiency of 0.67.

†If it is assumed that the energy density of 1 lb of jet fuel is 18,400 Btu and that of gasoline is 20,000 Btu, then $9 \times (8500$ lb/hr $\times$ 18,400 Btu/lb$) \times 24$ hr/day/(20 lb/man/day $\times$ 20,000 Btu/lb$) \times 1000$ men = 85 days equivalent gasoline supply is consumed daily in air collection.

dioxide extracted by combustion, or carbon dioxide can be removed as a gas directly by the addition of acid to the water. Carbonate concentration in the Atlantic and Pacific Oceans is about 100 ppm by weight.[17] Carbon dioxide comprises 73 percent of the carbonate ion. At a 100 percent extraction efficiency, 130 million gal of water must be processed daily to provide the required 78,800 lb of carbon dioxide. Volumes of the magnitude of 200 million gal are fed through the Washington, D. C., water system each day.[9] Thus the logistic burden associated with the establishment of an overseas facility capable of processing this volume of water for a 1000-man force makes this method of carbon dioxide generation impractical.

Another method of obtaining the carbon dioxide necessary for bioelectrochemical synthesis of methane is the combustion of fuel oil. Such oil contains about 15 percent carbon dioxide on a dry gas basis.[18] To obtain the 78.8 lb of carbon dioxide per man per day, 78.8/0.15 = 525 lb of oil are required per day, far above the average fuel requirement of 20 lb/man/day. Assuming that fuel oil is available in a TO, this use of fuel is obviously wasteful. The oil can be more effectively employed in conventional ways.

Wood, like petroleum fuels and mineral carbonates, can be burned to release carbon dioxide. If 1 kg of wood is burned to completion, 4.6 cu m[19] of gas is produced containing 17 percent (0.78 cu m) of carbon dioxide.[20] On a weight basis, 1 lb of wood yields 1.4 lb of carbon dioxide when burned.* To provide 78.8 lb of carbon dioxide per man, 78.8/1.4 = 56 lb of wood must be burned daily. This amounts to 28 tons daily for 1000 men. This is a much lower wood requirement than that in the methane fermentation system and might prove operationally attractive. Requirements in men, vehicles, and curb weight are discussed in the operational analysis.

Limestone and dolomite deposits, found in regions scattered over the world, are sources of calcium carbonate and magnesium carbonate, respectively.[15] When these minerals are burned, carbon dioxide, water, and various other gases are released. To supply sufficient carbon dioxide for the synthesis of methane for a 1000-man force, 78,800/0.26 = 303,000 lb or about 150 tons of rock must be processed daily. A large machinery outlay is not necessary for mining operations of this size; the minerals can be processed by hand.[5]

Water. Bioelectrochemical reactions are quite different from classical molecular reactions.[4] In such a system the enzyme reactive sites are merely used for initiating carbon dioxide reduction. It is not essential that microbial populations grow at the maximum rate as is necessary in fermentation processes. Theoretically, maximum methane output could be obtained even if all cells were in a dormant or resting state.[4] Nutrient requirements are very small, and the water requirement, on a weight basis, is estimated to be two to three orders of magnitude smaller than the carbon dioxide requirement.[4] It is therefore assumed that about 800 lb of water per day is required.

Electrical Power. On the basis of 9 kwh/lb of methane produced, the electrical power required to provide methane daily for a 1000-man force is

*Converting cubic meters of gas to cubic feet, 0.78 cu m × 35.3 = 26.7 cu ft of carbon dioxide are released when 1 kg of wood is burned. If carbon dioxide has a density of 0.12 lb/cu ft under standard conditions, then the above volume of gas weighs 26.7 × 0.12 = 3.2 lb. One kilogram equals 2.2 lb, so that from 2.2 lb of wood burned 3.2 lb of carbon dioxide is produced, or 1.4 lb of carbon dioxide per pound of wood.

$1000 \times 19 \times 9 = 171{,}000$ kwh. In electrical energy this is $171{,}000/24 = 7200$ kw or 7.2 Mw. The average Army energy requirement for 1000 men is 4×10^8 Btu/day and is equivalent to a daily electrical power requirement of 400,000,000/3413 = 117,000 kwh, or 4.9 Mw electrical energy (117,000/1000/24). Thus the minimum energy required for bioelectrochemical synthesis alone amounts to $7.2/4.9 \times 100 = 147$ percent of the Army total energy requirement. Electrical generators or nuclear reactors can be used to provide electrical power.

BIOSYNTHESIS OF ETHYL ALCOHOL

Alcohol may be obtained through the fermentation of naturally occurring organic substances such as grain, wood, potatoes, and other fleshy plant parts, and waste liquors from wood pulping operations. Starch from grain can be converted to easily fermentable moieties by concentrated enzymes or by mild acid hydrolysis and heating. However, cellulose, which is the predominant carbohydrate in woody-plant material, is not easily converted to fermentable sugars and must be hydrolyzed in very strong acid at about 150 lb of steam pressure. Under ordinary conditions of dilute acid hydrolysis the sugar yield from starch is about 3 times that from cellulose.[3] The extreme conditions necessary for conversion of wood cellulose require the use of bulky processing equipment. Nevertheless, potential alcohol yields from wood are discussed herein.

The production of alcohol from the fermentation of leafy plant material is worthy of consideration because certain potential areas of military operations are characterized by a superfluity of readily available lush vegetation.

Regardless of the kind of substrate used in alcohol fermentation, the alcohol concentration at the end of fermentation is very low (4 to 6 percent), and this dictates that a large volume of water must be heated above the boiling point of alcohol (78.3 °C) before distillation begins. Solution preheating and large high-temperature and high-pressure distillers are necessary for most efficient alcohol purification. For every pound of alcohol purified, approximately 21,000 Btu of energy is required.* If purified product alcohol were considered as fuel for distillation machinery, 1.7 lb of alcohol would be required for every pound of alcohol purified. Obviously, some other fuel or source of power is required for distillation. In this case a nuclear reactor could serve as a power source.

Alcohol from Cereals

Before alcohol fermentation is possible the starch of cereals must be converted to fermentable sugars such as glucose or maltose. This transformation is presented as four steps: (a) hydration of starch (enhanced by milling the grain prior to adding water), (b) gelatinization of starch (necessary before starch can be hydrolyzed), (c) enzymic (or acid) hydrolysis of starch to fermentable carbohydrates, and (d) the conversion of sugars to alcohol by yeast fermentation.[3]

*Industrially, 11 lb of coal is required to supply energy for distillation of 1 gal of ethyl alcohol.[21] The average heat content of 1 lb of coal is 12,500 Btu,[8] so that $12{,}500 \times 11/(6.6$ lb/gal$) = 20{,}900$ Btu is necessary to distill 1 lb of alcohol with a heat content of 12,700 Btu.

The long-chain starch molecules can be efficiently converted to fermentable sugars by saturation with water. Grain milling therefore enhances water uptake. Next the hydrated starch is gelatinized. This treatment breaks down starch molecules into simpler polysaccharides and is done industrially by heating at about 150°F for 30 min.[3] Gelatinization may also be accomplished by using concentrated preparations of the enzyme dextrase.[22] Although this technique has not been fully investigated as a means of eliminating the heating requirement, it is assumed that for 1965–1975 enzymic gelatinization of starch will be feasible.

Gelatinization of starch to polysaccharides alone does not permit fermentation, since yeast enzymes are incapable of attacking these molecules. Malt slurries and/or acid must be added to convert the polysaccharides to glucose, maltose, and certain dextrins. The sugars then can be converted to ethyl alcohol and carbon dioxide after inoculating the medium with yeast. An additional 15 gal of water per bushel of grain is added during the steps that follow hydration, amounting to a total water requirement of 40 gal per bushel of grain fermented.[3]

In this discussion, grain alcohol yields are taken collectively as an average for corn, wheat, rice, barley, oats, and sorghum, amounting to 2.5 gal per bushel of grain (56 lb) fermented.[23] This yield figure is the basis for deriving grain requirements to match the daily gasoline requirement for a military force. It is assumed that a field-scale batchwise process, with minimal equipment and power requirements, is feasible. Since continuous-feed fermentation systems in the whiskey industry run on 14-hr cycles,[23] it is reasonable to assume that a batch-type field-scale operation would require fermentation cycles of no longer than 24 hr.

The amount of energy available per pound of grain fermented is based on the heat of combustion (12,700 Btu/lb) of the product alcohol produced at the rate of 2.5 gal/bu/day. Ethyl alcohol has a density of 6.6 lb/gal. Therefore this raw material produces energy in synthesis alcohol at the rate of $2.5/56 \times 6.6 \times 12{,}700 = 3600$ Btu/lb/day.

To produce alcohol equivalent to 20 lb of gasoline/man/day, 20,000 Btu/lb $\times$ 20/3600 = 112 lb/man/day must be fermented. In other words, from the 2 bushels of grain, $5 \times 6.6 = 33$ lb of ethyl alcohol must be produced daily to supply the equivalent gasoline energy.

Water is required for the starch hydration, cooking, and conversion operations, and this amounts to about 40 gal/bu.[3] Since the estimated grain requirement is 2 bu/man/day, the water requirement will be $2 \times 40 = 80$ gal/man/day. This is over 3 times the Army waste-water allotment of 25 gal/man/day.

Powered equipment is necessary to mill grain so that water uptake is enhanced. This can be accomplished in the field using commercially available truck-mounted hammermills.

Large plastic-lined pits are sufficient to contain the water and grain slurry during the hydration and conversion process. Since heat-requiring operations are precluded in this analysis, large pressurized metal tanks and heating units are not necessary. The pit in which the prefermentation treatments are carried out may also serve for fermentation. The amount of earthmoving equipment required to dig these pits is computed.

Other appurtenances such as conveyors, circulation pumps, distillation apparatus, and storage tanks are necessary for field-type facilities. Such details are beyond the scope of this report; only the gross requirements and characteristics most likely to affect feasibility are discussed.

Alcohol from Wood

The world's most plentiful organic raw materials are sugars, starch, and cellulose. Cellulose is decidedly the most abundant but is the least useful for industrial fermentations. Wood waste from the lumbering industry contains as much as 50 percent cellulose.[3] As mentioned previously, cellulose must be converted to fermentable sugars prior to alcohol fermentation. Since cellulose is rather resistant to hydrolysis, extreme and somewhat costly treatment is necessary.

As with methane fermentation of wood, alcohol fermentation is also an inefficient method of obtaining heat energy. The heat of combustion of wood averages 8600 Btu/lb,[8] and through alcohol fermentation 1 lb of wood produces 0.16 lb of ethyl alcohol; hence $0.16 \times 12{,}700 = 2000$ Btu are available in the alcohol produced from 1 lb of wood.

Wood cellulose is hydrolyzed by two major processes: strong-acid methods and dilute-acid methods.[3] Heating to about 150°F is necessary in both processes. In strong-acid processes a large quantity of reagent is necessary, but yields are high and the product is free of undesirable by-products. In dilute-acid methods much less reagent is necessary, but yields are lower and the product is accompanied by undesirable contaminants. Field-type processing plants should be mobile and uncomplicated, but present-day acid hydrolysis systems are complex. Certain plants are capable of batch-type extraction, and others are equipped for countercurrent extraction in which large extraction vats are arranged in parallel. Thus saccharification processes and residue washing to remove acid can occur simultaneously.[3]

Certain organisms possess the enzyme cellulase, which is capable of converting cellulose to sugar. If heat-acid hydrolysis were replaced by enzyme hydrolysis, heating requirements would be minimized and the sugar extraction process would be simplified. The time required for acid hydrolysis of cellulose is about 3 hr.[3] Rates of enzyme hydrolysis probably will never be this high. Nevertheless it is assumed that enzyme hydrolysis will be attractive during 1965–1975. It is also assumed that the alcohol production cycle takes no longer than 24 hr.

Yields of potentially fermentable sugars from various woods range from 40 to 60 percent.[3] The average yield is 52 percent. It is assumed that 51 percent of the sugar is fermented to ethyl alcohol.

As stated previously, 33 lb of ethyl alcohol must be produced daily to equal the energy content of 20 lb of gasoline. To meet the average daily per capita fuel requirement, $33/(0.51 \times 0.52) = 125$ lb of wood must be fermented. For a 1000-man force this amounts to 63 tons/day.

The amount of water necessary for an adequate fermentation rate is taken to be that required to fill the "dead spaces" among the wood chips. If 63 tons of chips with a density of 17 lb/cu ft are required for 1000 men, then a volume of $63 \times 2000/17 = 7400$ cu ft is necessary for containment. Since two-thirds of this volume is "dead space," then the amount of water required (density:

7.5 gal/cu ft) is $7400 \times 2/3 \times 7.5 = 37{,}000$ gal/day. This is about 1.5 times the Army waste-water allotment for 1000 men.

Alcohol from Plant Foliage

As with fermentation of grain, the starch in plant foliage must be converted to fermentable sugars prior to addition of yeast. The starch content of plant foliage varies not only with species but also with time of day and season of the year. Because of this variability, only an average alcohol yield is calculated. Since no information is available on the foliage solids and water required for alcohol fermentation of leafy tissue, no attempt is made to determine water requirements and fermentor volumes for field-scale fermentation of plant foliage.

To facilitate analysis it is assumed that all carbohydrate present is converted to the sugar glucose. For each mol of glucose (180 g) fermented, 2 mols of carbon dioxide (88 g) and 2 mols of ethyl alcohol (92 g) are formed. Thus $92/180 \times 100 = 51$ percent of the carbohydrate is converted to alcohol.

From data on the carbohydrate content of the green tissues of several plant species,[23] an average value of 3.5 percent carbohydrate was obtained. For this analysis, therefore, it is assumed that carbohydrates constitute 3.5 percent of the fresh weight of leafy tissue.

If 3.5 percent of green tissue is carbohydrate and if 51 percent of the carbohydrate is theoretically converted to ethyl alcohol, then $0.035 \times 0.51 \times 100 = 1.8$ percent of the tissue is potential alcohol. In other words, 1 lb of foliage produces 0.02 lb of alcohol.

The alcohol required for the gasoline equivalent is 400,000 Btu/12,700 Btu/lb = 33 lb/man/day. Thus $33/0.018 = 1700$ lb of leafy tissue must be fermented per capita daily; for a 1000-man force 850 tons must be fermented daily. Such a requirement poses a more formidable equipment and manpower problem than the wood-methane operations. Because this system has low potential as an alcohol source, no operational aspects are considered.

OPERATIONAL CONSIDERATIONS

The operational feasibility of the various biosynthetic systems is investigated in the light of technological considerations made in previous sections. The quantity of fuel available from a given substrate is important and must be sufficient to meet the needs of a military force in the field. It is equally important to determine whether certain raw materials can be obtained and, if so, whether the requirements in manpower, equipment, and time enhance or detract from the operational attractiveness of a given system. Time is critical under circumstances where the fuel production system must move with user units. In other situations fuel synthesis complexes might be located in large cities within the theater; steady-state fuel production is possible and lead time is not important.

METHANE FROM WOOD

Collecting and processing 530 tons of wood require a large amount of manpower and machinery. After timber is cut it must be hauled to processing centers where the wood is chipped by engine-driven chippers into sizes suitable for fermentation. Some timber will be too large for admission to the chippers, so some sort of engine-driven milling machinery is required to reduce the timber to suitable size. Once methane is produced it must be distributed. The number of men and trucks required for methane production and distribution are compared with those for a gasoline supply system.

Overseas deployment of a military force using methane produced biochemically from wood involves earth-moving, log-transporting, wood-chipping, liquefaction, and wood-stirring equipment.

Wood Availability

Military operations may be required in any region of the globe. Since the geographic distribution of forests and jungles is not uniform, a fuel (methane) biosynthesized from wood would not be universally available. The forest areas of significance in Western Europe are the Grenoble, Dijon, Bordeaux, Bas-Rhin, and Haut-Rhin regions of France;[24] areas in Bavaria, the Black Forest, and the Ardennes of Germany; and scattered areas in the Benelux Countries, Spain, and Portugal. Northern and central Italy have ample forests, but southern Italy has scattered scrub forests only. Relatively large temperate broadleaf and mixed forests are found in Korea, Japan, southeast China, and

Romania. Large coniferous forests are found in the Alps, Carpathians, northern Russia, Finland, Sweden, and Poland. The coniferous forests of Alaska are among the finest found anywhere. Extensive mangrove swamp forests are prominent in coastal areas of Southeast Asia, with semideciduous, tropical forests predominating in the monsoon regions. In large areas of Central Africa forest savanna and grass savanna predominate; tropical rain forests exist in the remainder of Africa, except for the great northern desert regions. Complex, tropical rain forests are found in the Amazon Basin of South America and in Central America. Only scattered stands of desert scrub growth predominate in the Arabian Peninsula, Iran, and Iraq.[25]

Thus abundant methane resources exist in many regions of the world, but many important areas have little or no production potential. Furthermore the economy of some nations rests largely on their timber industry; protracted logging operations by US military forces could have serious economic and political consequences.

Start-up Time

A military force prepared to use methane as a fuel in a theater must wait approximately 4 days before methane is available from theater-based wood fermentation plants. Approximately 2 days are required for logging, chipping, digging, preparing, and filling the digestor pits. A third day is needed for methane accumulation. Under ideal circumstances, therefore, methane might be available by the fourth day. Because of this production lag time, a minimum 3-day supply of fuel must accompany a military force.

Fermentation Detention Time

One volume of digestor filled with wood chips produces 10 volumes of methane per day.[7] "Green" timber has an average density of 50 lb/cu ft.[26] Since chipped wood occupies a larger volume it weighs only 17 lb/cu ft, so that 100 lb of chipped wood occupies a volume of 6 cu ft. This volume of chips produces approximately 60 cu ft of methane gas per day or approximately 2.7 lb/day. As noted previously, 1 lb of wood has a theoretical yield of 0.18 lb of methane (18 lb per 100 lb of wood). At this rate 18/2.7 = 7 days are required for complete liberation of methane. This is an optimistic estimate of detention period. Research on high-rate digestion shows that at least 10 days are necessary for complete decomposition of volatile matter,[27] so that the 10-day period is viewed as a realistic detention period.

Manpower and Equipment

Industrial timber operations provide an estimate of manpower and equipment requirements.[28] The data used are average values; specific production rates and equipment requirements are affected by geographical factors.

Logging. In the US, timber is logged at an average rate of 1300 bd ft/man/day.[28] Freshly cut timber has an average density of 50 lb/cu ft and 1 bd ft of unmilled timber has a volume of 1/6 cu ft. Such timber therefore weighs (50/6) = 8.3 lb/bd ft and $1300 \times 8.3/2000 = 5.4$ tons/man/day is an average logging capability. The manpower necessary to obtain sufficient wood for the 1-day fuel requirement the first day is 530/5.4 = 98 man-days.

During the initial detention period, sufficient wood for the following production cycle can be accumulated at the daily rate of one-tenth the initial logging requirement. The manpower required to accumulate wood at this rate is therefore about 10 men.

Milling. Tree branches and leaves can be fed directly to chipping machines, but logs must be milled to plank or beam size before chipping. Wood is milled in the US at the rate of 1000 bd ft/man/day (4.1 tons/man/day).[28] To mill the timber required for start-up, 530/4.1 = 130 man-days are needed. Timber milling to accumulate wood daily for the succeeding fermentation cycle requires 13 men/day.

US Forest Service experience shows that wood chipping is done at the average rate of 1000 bd ft/man/day.[28] Thus the wood-chipping capability is $8.3 \times 1000/2000 = 4.1$ tons/man/day. Preparation of wood chips for start-up of a methane facility requires 130 man-days. Wood may be chipped during the initial 10-day fermentation cycle at a rate sufficient to accumulate substrate for the following cycle. This daily rate is one-tenth the initial wood-chipping requirement and requires 13 men/day.

The manpower requirements for digestor start-up are given in Table 1. A total of 368 man-days is required for this operation. Subsequent daily operations (with no need for earth moving and digestor filling) require 358/10 = 36 men. Movement of troops away from methane sources requires construction and start-up of new digestor pits. These operations require an additional 368 man-days of effort.

TABLE 1

MANPOWER REQUIRED FOR METHANE DIGESTOR START-UP
(For 1000 men supported)

Operation	Man-days
Logging	98
Milling	130
Wood chipping	130
Earth moving and digestor filling	10[a]
Total	368

[a]RAC estimate.

Fuel Distribution. Although biosynthesized fuel is produced in the area of operations and not subject to intertheater transport losses, methane distribution within the area must be considered. Four 2½-ton trucks are necessary to haul 10 tons of gasoline daily, assuming one round trip per day. Since 1.7 volumes of liquid methane equal 1 volume of gasoline in energy content (App A), $1.7 \times 4 = 7$ trucks are necessary to supply methane. If two men (driver plus helper) are assigned per vehicle, then 14 men are required for distribution. The daily manpower requirement is, therefore, 36 + 14 = 50 men.

Earth Moving. To determine the requirement for earth movers to prepare digestor pits, the volume of the pits must be known. As calculated previously, a 530-ton batch of wood chips with a density of 17 lb/cu ft is needed for a methane facility to supply 1000 men. This weight corresponds to a digestor-pit volume of $530 \times 2000/17 = 62{,}000$ cu ft.

The "Number 4" D-7 full-tracked tractor is assumed available for digestor-pit construction. This tractor has an earth-moving capacity of about 65 cu yd/hr.[29] It is also assumed that the required pits can be constructed in 10 hr. The number of tractors needed is $62{,}000/(65 \times 27 \times 10) = 3$. These tractors weigh 20 tons each, so that total tractor tonnage is 60 tons.

Wood Hauling. The number of vehicles required to haul wood for digestor start-up and subsequent daily operations is important. It is assumed that $2\frac{1}{2}$-ton trucks can make two round trips each day loaded to off-highway capacity (5000 lb). At this rate $530/(2.5 \times 2) = 106$ trucks are required to supply wood.

Wood Chipping. Commercial wood chippers can be used in the chipping operation. Small 5-hp chippers process wood at the rate of about 1000 lb/hr.[30] Larger machines can chip 10 tons of wood per day. At the higher rate about $530/10 = 53$ machine-days are required to process sufficient raw material for start-up. Commercial chippers have an average weight of 3000 lb each,[30] so that chipper tonnage is $3000 \times 53/2000 = 80$ tons.

Fuel Liquefaction. The Army has no equipment designed specifically for the liquefaction of methane, but it does have mobile, van-mounted air and hydrogen liquefiers.[14] These liquefiers weigh about 16 tons, and a mobile methane liquefier may weigh roughly the same. One such unit should be sufficient to process daily the methane required by a 1000-man force.[6]

TABLE 2

VEHICLE REQUIREMENTS
(2½-ton trucks for 1000 men supported)

Activity	Fuel system	
	Methane	Gasoline
Wood hauling	106	—
Methane hauling[a]	7	—
Gasoline hauling[b]	—	4
Total	113	4

[a]Based on 1.7 volumes per volume of POL; assumes vehicles are volume limited only.
[b]Based on distribution of 10 tons/day.

About twice as many trucks are required for methane distribution as for gasoline distribution (see Table 2). The total truck requirement for the methane system is almost 30 times as great as the number required for the gasoline system. Wood collecting (after digestor start-up) proceeds at one-tenth the start-up rate, so that only one-tenth of the wood hauling, chipping, and milling equipment is needed. Full demand for equipment occurs only when new digestors are constructed. For maximum system reliability this equipment must be attached to the fuel-production complex. Most of this equipment would remain idle following start-up, so that optimum general use of this equipment is not obtained.

In Table 3 the tonnage of trucks is added to the other equipment necessary for digestor start-up, making a total tonnage of 876 tons. At the rate of 1 ton/man

for ordinary supplies and equipment the curb weight for a 1000-man force is 1000 tons. Thus the transport of methane start-up equipment overseas increases curb-weight allowances by 88 percent. This extra tonnage in equipment could well be extra fuel; 876 tons of gasoline would support a 1000-man force under average conditions for almost 3 months.

TABLE 3

DIGESTOR START-UP EQUIPMENT

Equipment	Weight, tons
Earth movers	60
Wood chippers	80
Methane liquefier	16
Methane and wood haulers (2½-ton trucks)	720[31]
Total	876

Water Requirement

When timber is chipped its volume is increased to 3 times that of unchipped timber. Therefore two-thirds of the volume of a digestor filled with wood chips is "dead space." To provide the moisture necessary for methane formation this space can be filled with water. This mass of wood chips saturated with water has a solids concentration of 33 percent, but methane output is only appreciable up to 10 percent solids; drastic reductions in gas evolution occur beyond this concentration. However, further research on manipulation of solids may produce appreciable yields up to 40 percent solids concentration.[32]

If wood digestors are located in base or reserve areas of a TO, waste water from hospitals, kitchens, and latrines can supply water for methane production. However, such water sources are grossly insufficient. The air space in a digestor filled to start-up capacity is about $62{,}000 \times 2/3 = 41{,}600$ cu ft. Therefore about 300,000 gal of water are required to fill this "dead space." About 25 gal/man/day are required for waste disposal in a TO (25,000 gal/day for 1000 men).[33] About 10 times this daily water consumption is needed for digestor start-up the first day. Many possible areas of military operations are arid; deep wells are the only sources of water. Water requirements therefore place further geographic limitations on military forces that rely on methane from wood fermentation.

Conclusions

Methane fermentation of wood is a slow process. Since about 10 days is required to obtain a practicable yield, a tenfold increase in the raw-material input will permit production of the required amount of fuel in 1 day. Thus, much additional equipment and support personnel must accompany initial buildup supplies and troops into an area of operations.

The raw materials, wood and water, are not uniformly distributed geographically. In many areas a paucity of one or both of these raw materials

precludes methane production and military operations relying on methane produced in the field.

This system has many phases: logging, milling, wood chipping, water collection, fermentor operation, fuel purification and liquefaction, and fuel supply. Thus the threat of attack or interdiction at any point in the system flow sequence makes the operation an unreliable means of providing fuel.

Methane fermentation of wood is therefore an unattractive means of producing fuel in the field for military forces, and it is improbable that any further improvements will be sufficient to make the system attractive.

BIOELECTROCHEMICAL SYNTHESIS OF METHANE

To obtain the large quantities of carbon dioxide necessary for the bioelectrochemical synthesis of methane, resources rich in carbon dioxide are desirable. From the standpoint of theoretical carbon dioxide content, mineral deposits and wood are the most attractive sources, but from the standpoint of world distribution, minerals and/or wood are not available in important areas. A system capable of processing both raw materials would not only be more flexible than a single-substrate system but would also be available for military operations in more areas of the world.

It is unattractive to consider the intertheater transport of 40 tons of pure carbon dioxide daily to avoid field-scale processing. If carbon dioxide can be shipped, POL can be shipped.

A methane-synthesis cell with the output capacity desired has not been constructed, and no estimates of system weight have been made. However, the volume-output ratio has been estimated and is of the order of 10 lb of methane per cubic foot of cell volume.[4] To produce the 19,000 lb of methane for 1000 men, a 1900-cu ft cell volume is therefore necessary. On this basis two cells, each with dimensions of 8 by 10 by 12 ft, should be ample. Cells of this size are transportable in present USAF cargo aircraft, provided the load is not weight limited.

Although the Army does not have equipment designed specifically for methane liquefaction, it does have mobile air and hydrogen liquefaction vans that weigh about 16 tons.[14] This weight must be added to the tonnage of trucks and other equipment required for a given carbon dioxide processing method in order to estimate the total weight for a bioelectrochemical system. No major redesign of this equipment is necessary for conversion to methane production.[6]

Carbon Dioxide from Mineral Deposits

A mining operation that processes 150 tons of ore daily is small scale by industrial standards. In fact, various steps in the process can be accomplished by hand if certain machinery is not available.[15] For example, ore-carrying vehicles can be loaded by hand and the kiln can be hand fed if tractor-mounted shovels are not available.

Prebuilt rotary kilns can be transported to an area of operations, or vertical kilns, constructed of the rock carbonate material itself, can be built on site.

TABLE 4

CARBONATE-MINING EQUIPMENT[15]
(For 1000 men supported)

Equipment	Use	Number required	Weight, tons
Crawler-tractor	Overburden removal and rock loading	1	15
Churn-drill	Drilling charge holes	1	1
Jackhammer	Rock crushing	1	1
Compressor	Power for drill and hammer	2	1
Blacksmith shop	Maintenance	1	1
2½-ton dump truck	Rock hauling	8[a]	56
Rotary kiln	Carbonate-rock combustion	1	30
Total			105

[a]RAC estimate; assumes 10 trips/day and short loading time.

TABLE 5

CARBONATE-PROCESSING MANPOWER
(Daily support for 1000 men)

Operation	Man-days
Overburden removal and rock loading[a]	1
Drilling, blasting, and rock crushing	3
Kiln filling	2
Truck driving	16
Total	22

[a]Assumes rock loading with tractor-mounted shovel; 10 additional man-days are required if material is hand loaded.[15]

Estimates of the amount of equipment necessary for this mining operation are shown in Table 4. The deposits may lie beneath overburden, which must be removed before the mining operation begins. Following overburden removal the rock must be broken to sizes suitable for handling. Preliminary fragmenting of the deposit could be accomplished by blasting. Jackhammers could then be used for further breaking to sizes suitable for truck loading and combustion-kiln filling. Rock carbonates are burned in rotary or vertical kilns, yielding an average of 26 percent carbon dioxide.[20] Prebuilt rotary kilns may accompany initial buildup supplies or may be built from the carbonate rock itself on site.

Estimates of the manpower required for this operation are shown in Table 5. The addition of 22 men for fuel production is modest compared with 368 men required for the methane wood-fermentation system (Table 1).

Carbon Dioxide from Combustion of Wood

It was determined previously that 28 tons of wood must be processed daily to supply sufficient carbon dioxide for methane synthesis. Wood-processing operations like those in the wood-fermentation system are used here. However, the wood-chipping step is deleted from this operation because milling alone is sufficient to reduce wood to sizes suitable for burning in a combustion kiln.

Logging. Logging in the US is done at the average daily rate of 1300 bd ft (5.4 tons)/man.[28] At this rate 28/5.4 = 5 man-days are required.

TABLE 6

MANPOWER REQUIREMENTS FOR CARBON DIOXIDE FROM WOOD COMBUSTION
(Daily support for 1000 men)

Activity	Manpower required, man-days
Logging	5
Milling	7
Wood hauling	12
Total	24

TABLE 7

EQUIPMENT REQUIREMENTS FOR CARBON DIOXIDE FROM WOOD COMBUSTION
(Daily support for 1000 men)

Equipment	Activity	Number required	Weight, tons
2½-ton trucks	Wood hauling	6	36
Rotary kiln	Wood combustion	1	30
Total		7	66

Milling. Timber is milled at the average rate of 1000 bd ft (4.1 tons)/ man-day.[28] To mill 28 tons of timber daily 28/4.1 = 7 man-days are needed.

Wood Hauling. Drivers and helpers are necessary to man the trucks used for wood hauling. If it is assumed that $2\frac{1}{2}$-ton dump trucks can carry 5000 lb of wood cross-country, then, at the rate of two round trips per operating day, $28/(2.5 \times 2) = 6$ trucks are necessary. Therefore, 12 men are required for wood hauling each day. Thus the total number of men required to process wood for carbon dioxide is 24 (Table 6).

Combustion Equipment. One 30-ton rotary kiln will burn the wood required for a 1000-man force.[15] Six trucks are required for wood hauling and add about 36 tons to overseas shipping weight. The shipping weight of equipment (Table 7) required for this method of producing carbon dioxide amounts

to 66 tons and must be added to the shipping tonnage allotted to the methane-synthesis cell, liquefaction equipment, and the fuel-distribution vehicles discussed previously.

Methane Distribution. To supply the gasoline equivalent in methane, seven $2\frac{1}{2}$-ton trucks and 14 men are required (see the section "Fuel Distribution"). These quantities must be added to the specific carbon dioxide processing operation to estimate overall manpower and machinery requirements for a given system.

Conclusions

If wood is the source of carbon dioxide, wood-processing operations like those in the methane-fermentation system are required. Although the amount of wood that must be processed is much less than that required in the methane-fermentation operation, system flow is almost the same as in the latter and therefore of comparable vulnerability.

Mining operations to obtain carbon dioxide from mineral deposits are also highly vulnerable to enemy action.

Certain potential areas of military operations lack the timber and/or the mineral resources for production of the required amount of carbon dioxide, thereby reducing the number of areas in which armed forces relying on this method of fuel production can operate.

More desirable methods of obtaining carbon dioxide are needed to make this means of producing methane attractive. Once carbon dioxide is available, however, methane can be quickly obtained.

BIOSYNTHESIS OF ALCOHOL

Although cereals and wood are the only substrates considered here for alcohol fermentation, many other plant products are rich in starch or sugar and are therefore potentially good alcohol sources. In certain areas of the world, rice is the major crop; in others, corn; elsewhere, potatoes.

Alcohol fermentation ceases when alcohol concentration reaches a level that inhibits further microbial growth. The alcohol concentration is nevertheless dilute, and large industrial distillation complexes are necessary to purify the product efficiently. Field-scale distillation apparatus compatible with such industrial facilities requires engineering design effort, which is not attempted here.

Alcohol from Cereals

It is assumed that indigenous labor and machinery are used for harvesting grain, or that previously harvested grain is taken from storage. Standard Army vehicles are used for all hauling operations and the specifications of commercially available grain-milling and earth-moving equipment are used in computing logistic requirements. Estimates are made of the manpower required for grain milling, earth moving, and fermentor operation; manpower requirements for truck operation are computed on the basis of one driver plus helper per vehicle.

Equipment. Equipment requirements are summarized in Table 8. To estimate the number of vehicles required for grain hauling, 112 lb of grain per man per day, or 56 tons of grain, must be hauled each day to process alcohol for a 1000-man force. If $2\frac{1}{2}$-ton trucks are used, $56/2.5 = 23$ are required, which weigh about 160 tons.

The 5-ton portable hammermill and truck are commercially available and can mill grain at the rate of 3 tons/hr.[34] At the rate of 112 lb/man/day, the number of such units operating 10 hr/day and required for a 1000-man force is 112 lb/man-day × 1000 men/2000 lb/ton/(3 ton/hr) × 10 hr/day = 2 units. The two hammermills add 10 tons to total curb weight.

TABLE 8

ALCOHOL-PROCESSING EQUIPMENT FOR CEREALS
(Daily support for 1000 men)

Equipment	Use	Number required	Weight, tons
$2\frac{1}{2}$-ton trucks	Grain hauling	23	160
Hammermill	Grain milling	2	10
D-7 tractor	Earth moving	1	15
$2\frac{1}{2}$-ton trucks	Alcohol hauling	6	36
Total		32	211

To compute earth-mover requirements for digging fermentor pits it is first necessary to determine the volume of soil that must be moved. This value is derived from calculation of the volume occupied by the grain and water necessary for a 1000-man force. Milled grain has a volume of 0.87 cu ft/bu.[22] At the rate of 2 bu/man/day, 0.87 × 2 = 1.74 cu ft will contain the daily per capita grain quota, or 1.74 × 1000 = 1740 cu ft for 1000 men.

One gallon of water occupies a volume of 0.134 cu ft. If 80 gal are required per man per day, then 80 × 100 × 0.134 = 10,700 cu ft are necessary for 1000 men daily. The total fermentation-pit volume required for grain and water is 1740 + 10,700 = 12,440 cu ft. New pits need not be constructed each day; an auger system may be built integral to the pit, permitting removal of the spent substrate prior to each daily run.

The number of D-7 crawler tractors is computed at an earth-moving capacity of 65 cu yd/hr for a 10-hr day.[29] Therefore, 12,440 cu ft/65 cu yd/hr/27 cu ft/cu yd × 10 hr/day = 1 tractor will meet the requirement for a 1000-man force and adds 15 tons to total curb weight.

Manpower. These requirements for processing raw material for construction and for fuel distribution appear in Table 9.

Grain hauling requires 46 men at the rate of two per truck.

If it is assumed that two men are required to operate a portable hammermill, the manpower requirement for milling is four.

One man (crawler-tractor driver) is sufficient to meet daily earth-moving requirements.

The manpower required for alcohol distribution remains the same as in the previous section, i.e., 12 men to operate 6 trucks each day.

No estimates are made of the manpower required for fermentor operation. The pits could be filled directly from dump trucks, thereby avoiding the need for additional men to hand-fill them. One man is probably required for monitoring distillation and collection equipment.

TABLE 9

ALCOHOL-PROCESSING MANPOWER FOR CEREALS
(Daily support for 1000 men)

Operation	Man-days
Grain hauling	46
Milling	4
Earth moving	1
Alcohol distribution	12
Total	63

TABLE 10

ALCOHOL-PROCESSING EQUIPMENT FOR WOOD
(Daily support for 1000 men)

Item	Use	Number required	Weight, tons
2½-ton truck	Wood hauling	13	78
Wood chipper	Wood chipping	6	9
D-7 tractor	Earth moving	0.4	6
2½-ton truck	Alcohol hauling	6[a]	36
Total			129

[a]Assumes vehicles are volume limited only.

Alcohol from Wood

The manpower and equipment requirements that are derived for logging, milling, wood chipping, and fuel distribution are presented in Tables 10 and 11.[26,28]

Wood Hauling. The $2\frac{1}{2}$-ton trucks required for hauling wood at the rate of 63 tons/day are assumed to be loaded to off-highway capacity (5000 lb) and to make two round trips per day. To haul wood for 1000 men, $63/2.5 \times 2 = 13$ trucks are necessary. The total weight of these vehicles is about 78 tons.

Wood Chipping. Chipping wood increases the total surface area exposed to degradation and thereby increases reaction rates. Large wood chippers process wood at the rate of 10 tons/day.[29] Therefore to chip wood for 1000 men

each day, 63/10 = 6 machines are required, having a total shipping weight of 9 tons.

Fermentors. Fermentation chambers can be fashioned from pits bulldozed in the soil by crawler tractors such as the D-7. If the required wood chips occupy a volume of 7400 cu ft and if the tractor can move soil at the rate of 65 cu yd/hr in a 10-hr operating day, 7400/65 × 27 cu ft/cu yd × 10 = 0.4 D-7 tractors are required. In other words, one D-7 tractor is capable of digging alcohol fermentation pits sufficient for 2500 men.

TABLE 11

ALCOHOL-PROCESSING MANPOWER FOR WOOD

(Daily support for 1000 men)

Operation	Man-days
Logging	12
Milling	16
Wood hauling	26
Wood chipping	16
Alcohol distribution	12
Total	82

Fuel Distribution. It is assumed that $2\frac{1}{2}$-ton trucks are used for alcohol hauling, that they are loaded to volume capacity, and that they make two round trips per day. Four $2\frac{1}{2}$-ton trucks are required to haul the daily gasoline allotment for 1000 men (Table 2). Since about 1.4 volumes of ethyl alcohol have the energy equivalent of one volume of gasoline (App A), about 6 trucks are required.

Logging Manpower. In logging operations timber is cut, trimmed, and moved to local distribution points in the US at the rate of 1300 bd ft (5.4 tons)/man-day.[28] To log timber that produces sufficient alcohol for 1000 men daily, 63/5.4 = 12 man-days are required.

Milling Manpower. Timber is milled at the rate of 4.1 tons/man/day.[28] To reduce the above amount of timber to sizes suitable for chipping, 63/4.1 = 16 man-days are necessary.

At the rate of two men (driver plus helper) per truck the wood-hauling manpower required is 26 men.

US Forest Service data indicate that wood is chipped at the rate of 4.1 tons/man/day.[28] At this rate 63/4.1 = 16 man-days are required for this operation.

As for methane, alcohol distribution within the area of operations is important, and it is necessary to estimate the number of men and trucks required for supply. It is assumed that each truck makes one round trip per day and that four $2\frac{1}{2}$-ton trucks can deliver the gasoline required by 1000 men. About 1.4 volumes of ethyl alcohol have the energy content of 1 volume of gasoline (App A), so that 1.4 × 4 = 6 trucks are required for delivery of alcohol. At the rate of two men per truck, 12 men are required for distribution.

As in the previous section, no estimates are made of the manpower required for fermentor operation.

Conclusions

Alcohol can be obtained by fermentation of many types of raw material, but, like that obtained by methane fermentation, the fuel would not be quickly available for Army use.

This system consists of many phases, regardless of the type of raw material used. Much equipment and personnel are involved, and certain phases of the production cycle (e.g., collecting and processing raw material) are very vulnerable to enemy action.

A significant increase in initial supply tonnage would be necessary if a cereal-fermentation system were established overseas, but an insignificant increase in initial tonnage would result if a wood-fermentation system were used. (Increases greater than 20 percent are regarded as significant.) Significantly fewer support personnel are required to operate the cereal-fermentation system than are required to operate the wood-fermentation system.

The heat energy required to purify a given volume of ethyl alcohol by distillation is almost twice as much as the volumetric heat content of the product. If it were necessary to use product alcohol to power distillation equipment the amount of alcohol consumed in this process would be greater than the amount of fuel purified.

Alcohol fermentation is therefore an unattractive means of producing fuel in the field.

GENERAL REMARKS

The biosynthetic systems discussed in this paper are bulky and relatively immobile. In the bioelectrochemical system the biological cell, methane liquefier, and storage and delivery containers will probably be mobile. But the carbon dioxide processing equipment, whether for mining rock carbonate or combustion of wood, will be bulky and immobile. The methane and alcohol fermentation pits are also immobile, and their use reduces flexibility.

Transport of a synthesis facility overseas affects the initial curb weight. Initial curb weights are estimated at the rate of 1 ton/man. Thus the curb weight for a 1000-man force is about 1000 tons. Table 12 shows the additional increase in curb weight for the various systems discussed. The average daily hydrocarbon fuel requirement for support is 10 tons per 1000 men. The number of days of support, based on replacement of the equipment with an equal tonnage of fuel, is also shown.

In all the systems discussed in this paper the product is not available immediately on arrival in the area. A few days' supply of fuel must accompany the deployed forces, and a dual supply capability must be provided. Trade-offs between increased initial buildup effort and reduced fuel resupply effort are important and may be applied to specific TOs in which fuel is to be produced, but such analysis is not attempted in this paper.

TABLE 12

CURB WEIGHTS OF VARIOUS SYSTEMS

System	Weight, tons	Equivalent days of support with gasoline
Wood methane	876[a]	88
BEC[b] methane		
Carbonate mining	163[c]	16
Wood combustion	124[c]	12
Wood alcohol	145[d]	15
Cereal alcohol	227[d]	23

[a]Includes raw-material and fuel-processing equipment plus 16 tons for methane liquefier.

[b]Bioelectrochemical; no weight allowance for biological cells is included.

[c]Includes raw-material processing equipment plus 16 tons for methane liquefier and 42 tons for fuel delivery trucks.

[d]Includes raw-material processing equipment plus 36 tons for alcohol delivery trucks.

APPENDIXES

Appendix A

PROPERTIES OF SELECTED SUBSTANCES

DISCUSSION

The heat of combustion per unit weight and the heat of combustion per unit volume are two criteria for fuel attractiveness. A fuel may have a relatively high heat of combustion per pound, but, being of low density, may have a low volumetric heat of combustion. Hydrogen is an example of such a fuel (Table A1).

The major components of air (oxygen, nitrogen, and carbon dioxide) and sludge gas (methane and carbon dioxide) have discrete, well-separated boiling points. This characteristic is used advantageously in the low-temperature (cryogenic) purification of a given moiety.

TABLE A1

PROPERTIES OF SELECTED SUBSTANCES

Substance	Combustion heat		Liquid density, lb/cu ft	Boiling point, °C
	Btu/lb	Millions of Btu/cu ft		
Gasoline	20,200	0.85	42	—
Hydrogen, liquid	51,600	0.225	4.4	−253
Methane, liquid	21,000	0.556	26.5	−115
Methane, gas[a]	21,000	0.044	2.1	—
Carbon dioxide	—	—	94.4	−28.5
Oxygen	—	—	71.2	−133
Nitrogen	—	—	50.4	−146
Ethyl alcohol	12,740	0.629	49.4	78.3
Methyl alcohol	9,630	0.486	50.5	64.5

[a]750 psig.

Appendix B

ENERGY REQUIREMENTS FOR METHANE LIQUEFACTION AND PRESSURIZATION

DISCUSSION

The energy density of methane gas can be increased by either low-temperature liquefaction or by pressurization. Therefore the volume required for containment of a given amount of heat energy is much less for the liquid than for the gas.

To store or transport liquefied materials such as methane, efficient insulation material to minimize boil-off is required. New lightweight containers and insulation have been developed[6] so that the handling of low-temperature (cryogenic) materials has become less awkward.

About 3.5 kwh are required to liquefy 100 cu ft of methane from a gas mixture of 70 percent methane and 30 percent carbon dioxide.[6] The same apparatus also liquefies carbon dioxide, which is used for internal cooling.

In terms of heat energy, 3.5 kwh $\times$ 3413 Btu/kwh = 12,000 Btu are required to liquefy 100 cu ft, or 100 cu ft $\times$ 0.045 lb/cu ft = 4.5 lb of methane. About 2700 Btu (12,000/4.5) are required per pound of methane liquefied. In other words 2700/21,000 $\times$ 100 = 13 percent of the equivalent energy in a pound of the product is required for liquefaction. Once the purified product accumulates, a portion may be recycled to power liquefaction equipment. The output rating of the plant must be adjusted by the 13 percent factor to permit production of fuel to meet both the military requirement and the processing power requirement.

To compress 1 lb of methane gas under a pressure of 20 psig to a pressure of 750 psig requires 290 Btu.[5] If the compression equipment operates at 35 percent efficiency, 290/0.35 = 835 Btu are required to pressurize 1 lb of the gas; this is equivalent to 835/21,000 $\times$ 100 = 4 percent of the energy contained in the product. Again, use of the product to fuel the processing equipment dictates a 4 percent increase in output capacity to meet military fuel requirements.

Volumetrically, 1 gal of pressurized methane weighs 0.045 lb/cu ft $\times$ (750 psi + 14 psi)/14 psi $\times$ 0.134 cu ft/gal = 0.28 lb and 1 gal of liquefied methane weighs 0.134 cu ft/gal $\times$ 26.5 lb/cu ft = 3.6 lb. Therefore 1 gal of compressed methane has (0.28/3.6 $\times$ 21,000)/21,000 $\times$ 100 = 8 percent of the energy contained in 1 gal of liquid methane.

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